Rubidium lifetime in a dark magneto-optical trap

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Abstract

Measurements of rubidium lifetime in a dark magneto-optical trap (DMOT) was performed at various populations of the bright and dark hyperfine states of the trapped atoms. The rubidium lifetime in the trap appeared to be shorter if the atom spent more time in the bright state. A simple explanation of this effect is based on the increase of the cross-section of rubidium collisions with the surrounding warm atoms upon rubidium electronic excitation.

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INTRODUCTION

Laser cooling of neutral atoms in magneto-optical traps, MOT [1, 2] became an important technique of the modern atomic physics. MOT is a convenient and reliable apparatus for cooling large clouds of atoms to the temperatures in the 10 - 100 μK range. The main applications of MOTs include laser spectroscopy of cold atoms, cold collisions, new frequency standards, first stage of cooling to achieve BEC and many others.

There are well-known difficulties in straitforward applications of MOTs to the investigations of cold atoms. The MOTs use strong laser radiation and inhomogeneous magnetic field that disturb captured atoms. One way to solve this problem is to separate in time the capture and investigation of cold atoms. A disadvantage of this approach is that one has to work with unstable object, the atomic cloud released from the trap.

In some cases the problem can be solved with the help of a specially modified MOT, the dark magneto-optical trap (DMOT) proposed in [3] for alkali atoms. The DMOT consists of two regions. The outer region has both the trapping and repumping light and works similar to an ordinary MOT. In the inner region the repumping light is blocked and atoms are collected on the "dark" hyperfine state noninteracting with the trapping light. Because of the scattering of the repumping light by the optical elements and warm atoms a low intensity repumping light is nevertheless present in the inner region of DMOT. Consequently, some fraction of the trapped atoms is situated in the "bright" hyperfine state that interacts with the trapping light. Note, that the atoms in the "bright" state are responsible for the cloud fluorescence in DMOT.

Main application of DMOTs is for increasing the density of trapped atoms. It occurs because the particle repulsion induced by the radiation exchange and the rate of superelastic collisions are suppressed in DMOT. In addition to this useful ability of DMOT to hold large fraction of atoms in dark state, DMOT allows us to vary in a controllable way the populations of the bright and dark states. The populations of these states determine a number of processes in DMOT, e.g., the laser power absorbed by cold atoms. Thus the change of the fraction of "bright" atoms in DMOT can be used to study the physics of cold atoms. In this paper we report on an experimental observation of the lifetime dependence of rubidium atoms in a DMOT on the relative abundance of the bright and dark hyperfine states.

RUBIDIUM LEVEL SCHEME AND DMOT

Our experiment was done with ^{85}Rb atoms. The energy level diagram is presented in Fig.1. The DMOT used two lasers. The trapping laser frequency was tuned to the red by 15 - 20 MHz from the transition $F_g = 3 \rightarrow F_e = 4$. The frequency of the repumping laser was varied in a wide range in the vicinity of the transitions $F_g = 2 \rightarrow F_e = 2, 3$ (see below). The hyperfine states $F_g = 2$ and $F_g = 3$ are the dark and bright states, respectively.

An experimental setup is shown in Fig.2. Our DMOT collects atoms from surrounding warm rubidium vapour similar to the approach suggested in the Ref. [2]. The DMOT uses 6 circular polarized trapping beams and 2 linear polarized repumping beams all having diameter of approximately 15 mm and intensity 6 mW. The hollow repumping beams (inner diameter equal 5 mm) were directed to the trap center at 90^0 to each other. The trapping and repumping beams were produced by the two commercial lasers DL100 (Toptica).

Quadrupole magnetic field was created by two Helmholtz coils having 100 turns each, diameter equal 5 cm and separated by 5 cm. The coils produced in the trap center the magnetic field gradient equal 17 G/cm along the symmetry axis at the current through the coils equal 1.6 A. The quadrupole magnetic field could be switched on and off as fast as 500 μsec.

We have used simple vacuum chamber for DMOT that is a glass sphere of diameter 6 cm without antireflection coating. The chamber was permanently connected to the 5 liter/sec ion pump and to the glass appendix containing metal rubidium. The rubidium vapour pressure in the chamber was regulated by cooling this appendix with the help of Peltier element. Because the chamber was permanently pumped by the ion pump the rubidium vapour pressure was significantly lower than the saturated vapour pressure for a given appendix temperature. The pressure of residual gases in the chamber was on the order of 10^{-8} Torr.

The rubidium populations in the ground hyperfine states were measured in the experiment with the help of an additional probe beam that was produced by the free running (without an external resonator) home-made diode laser equipped with good quality current and temperature stabilizers. The diode ML6XX24 (Mitsubishi) was used in this laser. The linewidth of the probe radiation was estimated being less than 1 MHz (HWHM).

All three lasers used in the present experiment were equipped with the home-made frequency stabilization systems based on the DAVLL (dichroic atomic vapour laser lock) principle [4, 5]. This stabilization system allowed us to stabilize the radiation frequency at any point in a wide range ($\simeq$1 GHz) near each hyperfine Rb absorption lines. The system provided a good frequency stability with the laser frequency drift being less than 3 MHz/hour. More details on our stabilization system can be found in [6].

EXPERIMENTAL RESULTS

The steady-state number of captured rubidium atoms depends on the density of surrounding warm rubidium atoms. If the appendix containing metal rubidium was kept at room temperature, the total number of captured rubidium atoms in our DMOT exceeded $5 \cdot 10^8$. The cloud had almost spherical shape with the diameter 0.8 mm. The shape of the rubidium cloud was determined from the digitized fluorescence image recorded by the CCD video camera.

The density of captured rubidium atoms as a function of frequency of repumping radiation is presented in Fig. 3. These data were obtained with the rubidium appendix kept at room temperature. In order to determine the value of the repumping frequency the saturation absorption resonances of counter propagating beams in an additional rubidium cell (at room temperature) were recorded. These resonances for the hyperfine transitions $F_g = 2 \rightarrow F_e = 1, 2, 3$ are shown in Fig. 3a. Because there are three allowed transitions in the absorption spectra $F_g = 2 \rightarrow F_e = 1, 2, 3$, the saturation resonance spectrum has six peaks. Frequency calibration of this spectrum was performed using the tabulated positions of the resonances given in [7]. For convenience of the reader the frequencies of the saturated resonances are listed in Table I.

The Rb densities in the $F_g = 2$ state (n_2) and in the $F_g = 3$ state (n_3) at various repumping frequencies are presented in Fig. 3b. These data were recorded at slow scan rate of the repumping frequency in order to account the large filling time of the trap. The n_3 curve has two peaks at the repumping frequencies coinciding with the transitions $F_g = 2 \rightarrow F_e = 2, 3$. The n_2 curve has more complicated structure. For the following we need to consider in the n_2 curve the two positive wide peaks and the two negative narrow peaks all centered at the repumping frequencies of $F_g = 2 \rightarrow F_e = 2, 3$ transitions. The positive wide peaks in the n_2 and n_3 curves are due to the peaks in the efficiency of the

repumping radiation in the outer region of DMOT. The narrow negative peaks in the n_2 curve are due to the hyperfine pumping caused by the weak scattered repumping light in the inner region of DMOT. More details of this experiment and the discussion of the curves' features can be found in [8].

Let us consider now the ratio of the rubidium densities in $F_g = 3$ and $F_g = 2$ states, n_3/n_2, as a function of repumping frequency (Fig. 3c). The ratio n_3/n_2 has two maxima at the centers of $F_g = 2 \rightarrow F_e = 2, 3$ transitions. The ratio n_3/n_2 has deep minimum at the repumping frequency between the $F_g = 2 \rightarrow F_e = 2, 3$ transitions. Note that the DMOT capture remains highly efficient at all these repumping frequencies. The data in Fig. 3c shows that by tuning the repumping frequency the ratio n_3/n_2 in the DMOT can be varied from 1.5 to 0.08, thus by 20 times.

These features of our DMOT was used in the present experiment to measure the state dependence of the rubidium lifetime in the trap. We measured the number of trapped atoms in the $F_g = 2$ state as a function of time after switching on the quadrupole magnetic field at the three positions of repumping frequency, ω_{rep}:

$$\omega_{rep} = \omega_{22}, \quad \omega_{rep} = \omega_{23}, \quad \omega_{rep} = -40 \text{ MHz}, \tag{1}$$

where ω_{22} and ω_{23} are the frequencies of the $F_g = 2 \rightarrow F_e = 2, 3$ transitions, respectively. The number of trapped atoms was measured with the help of the probe beam absorption. The probe frequency was tuned to the center of the $F_g = 2 \rightarrow F_e = 1$ transition. This transition is a closed transition and thus experiences smaller power saturation that the two other allowed transitions started from the state $F_g = 2$.

The measurements were done at rubidium appendix temperature equal -8 C. This reduced significantly the rubidium pressure in the trap chamber and consequently the number of trapped atoms became 10 - 20 times smaller than for rubidium appendix being at the room temperature. The decrease of the number of trapped atoms simplified the experimental situation because the cloud appeared to be optically thin. On the other hand, it was checked that the ratio n_2/n_3 undergoes the similar variations with the change of ω_{rep} as in the Fig. 3c measured for the rubidium appendix at the room temperature.

The time dependencies of the number of captured atoms are presented in Fig. 4. The two curves ("a" and "b") corresponding to ω_{rep} being at the centers of the $F_g = 2 \rightarrow F_e = 2, 3$ transitions coincide completely with each other. The third curve for $\omega_{rep} = -40$ MHz

shows significantly longer lifetime. The measured lifetimes are,

$$\tau_{22} = 0.72 \pm 0.01 \text{ sec}; \quad \tau_{23} = 0.74 \pm 0.01 \text{ sec}; \quad \tau_{mid} = 1.03 \pm 0.01 \text{ sec}; \tag{2}$$

where indices refer to the position of the repumping frequency. The filling time dependencies presented in Fig. 4 appeared to be purely exponential at the experimental accuracy.

DISCUSSION

The lifetime of rubidium atoms in magneto-optical traps depends on many effects (see, e.g., the review [9]). One can neglect some of these effects at low density of captured atoms chosen in this experiment for the rubidium lifetime measurements. The fact that our filling curves were purely exponential supports the neglect of the reabsorption of rubidium fluorescence and superelastic collisions inside the cloud. In this simplified case, the number of trapped atoms, N, is governed by the following equation [2],

$$\frac{dN}{dt} = R - N\gamma, \tag{3}$$

where, R is the trap capture rate of rubidium atoms and γ is the escape rate of rubidium atoms from the trap. The rate γ is determined by the collisions with the surrounding warm atoms,

$$\gamma = n_{Rb}\sigma_{Rb}v_{Rb} + n_b\sigma_b v_b, \tag{4}$$

where n_{Rb}, n_b, are the concentrations of warm rubidium atoms and residual gases, v_{Rb}, v_b are their velocities. The cross-sections, σ_{Rb} and σ_b, characterize the collisions that accelerate cold atoms to the velocity larger than the critical velocity, v_c. Critical velocity is the maximum velocity of Rb atoms that trap is able to capture [2].

The model of Eq. (3) gives the exponential time dependence for the number of captured atoms with the time constant equal γ^{-1}. The observed in our experiment change in the rubidium lifetime at various repumping frequencies can be understood if one suggests that the cross-sections σ_{Rb} and σ_b depend on the electronic state of cold rubidium atom. Note that the times spent in the ground and in the electronically excited states of the trapped rubidium atoms differ significantly for the repumping frequencies equal ω_{22}, or ω_{23} and ω_{mid} chosen in this experiment. The measurements made above show that there are 60% of Rb atoms in the bright hyperfine state if ω_{rep} equals to ω_{22}, or ω_{23}, and only 10% if $\omega_{rep} = -40$ MHz. Rb atoms in the bright state spend approximately half of their time in

the excited state. Consequently, the fraction of the electronically excited Rb atoms equals $\simeq$30% if $\omega_{rep} = \omega_{22}$, or ω_{23} and $\simeq$5% if $\omega_{rep} = -40$ MHz. One can estimate that such variation of electronically excited Rb atoms can explain the change of lifetime given by Eq.(2) if an electronically excited Rb atom has its "escape" cross-section 3 times larger than an unexcited atom.

The state dependence of the rubidium cross-sections is the fact well established in the experiments devoted to the rubidium light-induced drift (LID) effect [10]. It was measured in Ref. [10] that the change in the rubidium transport cross-section can be as as large as 50%. Note also, that the losses in magneto-optical traps are dependent on similar but not identical cross-sections. The LID effect depends on the transport cross-section change upon atom excitation, but the trap losses are dependent on the cross-section of the transfer to the cold atom a small amount of kinetic energy sufficient for the atom to escape from the trap. This "escape" energy is by 2-3 orders of magnitude smaller than the k_BT at room temperature.

CONCLUSIONS

We have measured the rubidium lifetime in the dark magneto-optical trap (DMOT) at the relative populations of the bright and dark hyperfine states different by factor 20. The measurements showed that the rubidium lifetime in DMOT became shorter when it spent more time in the bright state. The possible explanation of this effect can be based on the assumption that the cross-section of trapped rubidium atoms with surrounding warm atoms is larger for the electronically excited rubidium than for rubidium in the ground state. Similar trend was observed previously for the transport cross-section of electronically excited rubidium atoms in the investigations of the light-induced drift effect (LID) [10].

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Frequency detuning (MHz)	-92.82	-78.11	-63.4	-46.41	-31.7	0
Transition	$2 \to 1$	$2 \to 1$	$2 \to 2$	$2 \to 1$	$2 \to 2$	$2 \to 3$
		$2 \to 2$		$2 \to 3$	$2 \to 3$	

Table I: Frequencies of the saturated absorption resonances in ^{85}Rb for the transitions started from the $F_g = 2$ hyperfine state [7]. The double transitions indicate the cross-resonances. Zero frequency detuning was chosen at the center of the F_g=2->$F_e = 3$ transition.

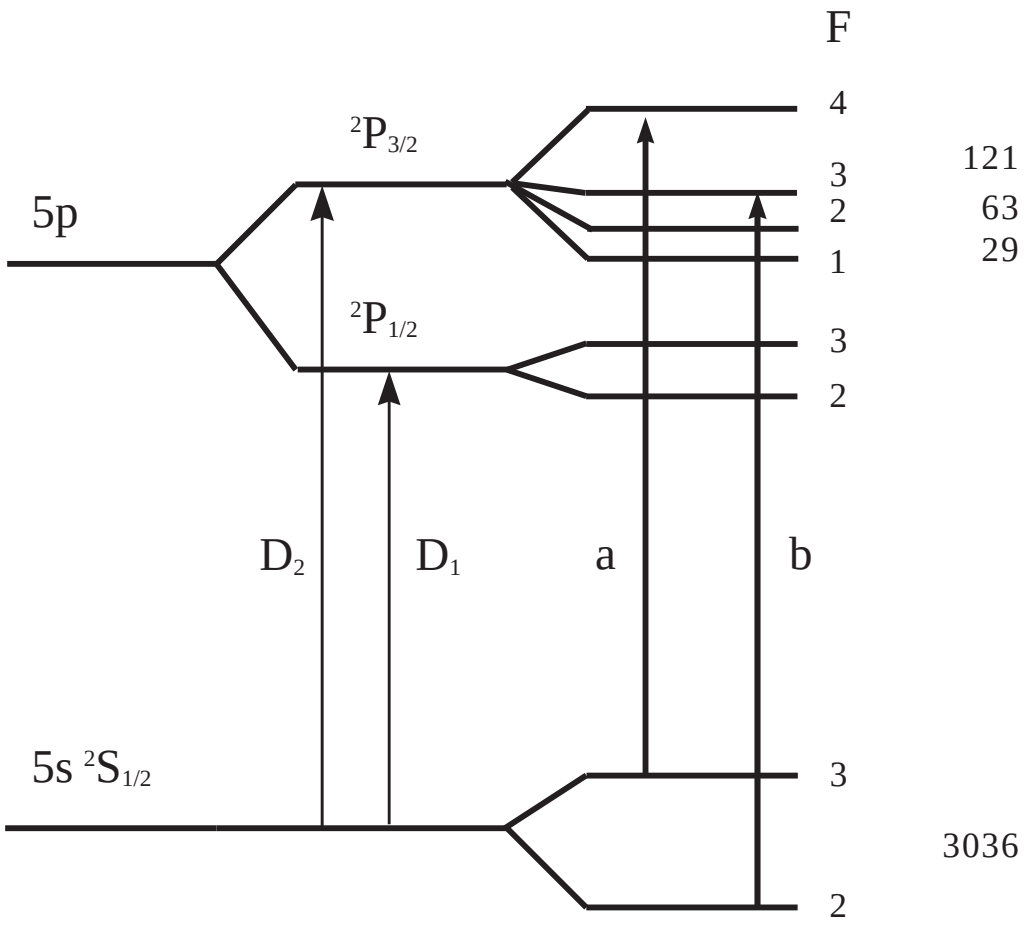

Figure 1: *Energy level diagram of* ^{85}Rb. *a - trapping radiation; b - repumping radiation. Numbers at the right side give the splittings of the hyperfine levels [7].*

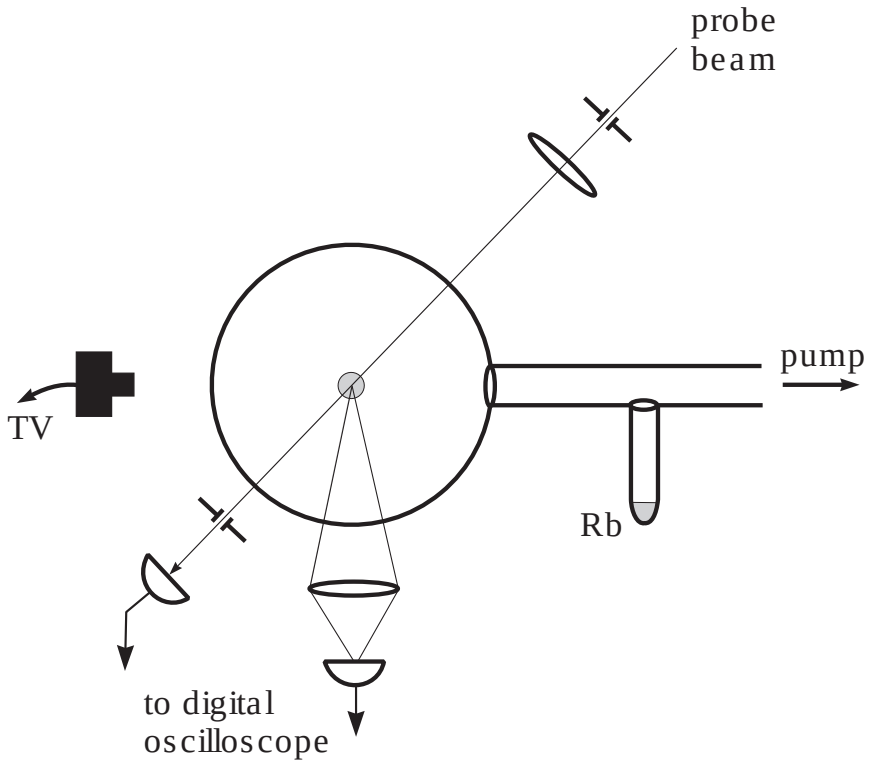

Figure 2: *Scheme of the measurements of the density of trapped rubidium atoms. The Helmholtz coils, trapping and repumping beams are not shown.*

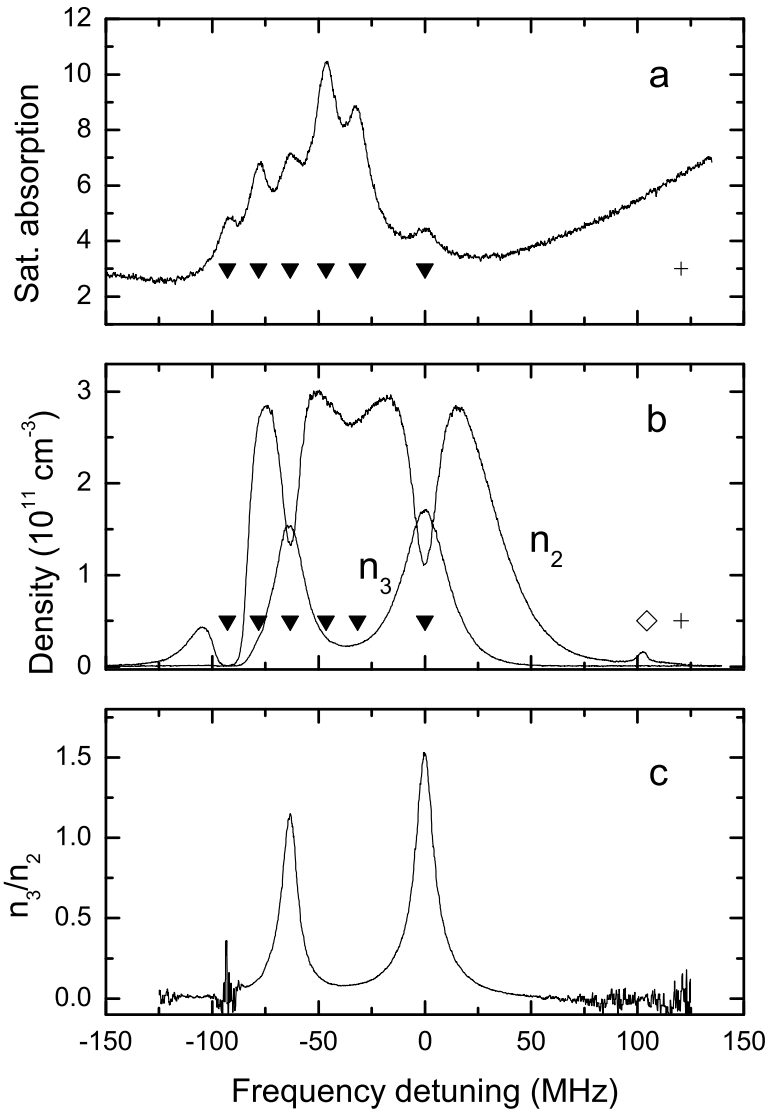

Figure 3: *Densities of rubidium atoms in the hyperfine states $F_g = 2$ and $F_g = 3$ as a function of repumping frequency. a - saturated resonances for the transitions $F_g = 2 \rightarrow F_e = 1, 2, 3$; b - densities in the states $F_g = 2$, (n_2) and $F_g = 3$, (n_3); c - ratio n_3/n_2. The signs indicate: ▼ - the positions of the saturated resonances [7]; + - center of the forbidden transition $F_g = 2 \rightarrow F_e = 4$; ◊ - position of the Raman resonance for the trapping and repumping radiations.*

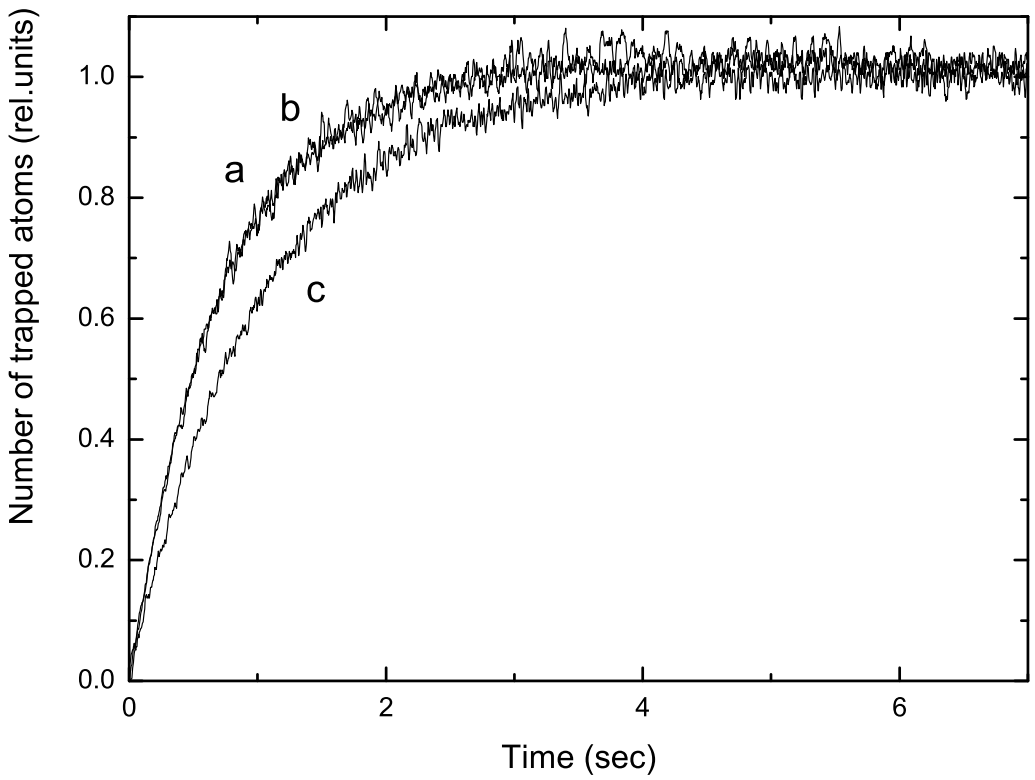

Figure 4: *The time dependences of the number of captured rubidium atoms for the three positions of the repumping frequency, ω_{rep}. Curve a: ω_{rep} is at the center of the $F_g = 2 \rightarrow F_e = 2$ transition; curve b: ω_{rep} is at the center of the $F_g = 2 \rightarrow F_e = 3$ transition; curve c: $\omega_{rep} = -40$ MHz.*